

Fein oder nicht fein

Adaptive Gitterverfeinerung in Brandsimulationen

December 13, 2016 | Marc Fehling | Civil Security & Traffic (CST)

Introduction

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Table of contents

Motivation

Modeling fires

Finite Element Method (FEM)

Adaptive Mesh Refinement (AMR)

High-performance computing on JURECA

Summary & Outlook

Unstructured grids

Motivation: Fire Safety

- Safety measures increase chance of survival of inhabitants in case of emergency.
- Fire safety measures:
 - Fire doors, building materials, smoke extraction, sprinklers, ...
- German legislation prescribes 'building codes'.

<ul style="list-style-type: none"> ▪ For 'normal' purposes: <ul style="list-style-type: none"> ▪ residential buildings 	<ul style="list-style-type: none"> ▪ For 'special' purposes: <ul style="list-style-type: none"> ▪ event halls ▪ malls ▪ garages ▪ accommodations ▪ factories ▪ skyscrapers ▪ ...
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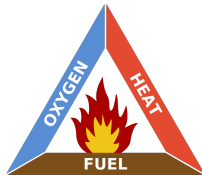


Figure: Fire triangle. (source: [wiki](#))

Motivation: Architecture

- Modern architecture and large-scale projects (like BER) may not fit in 'building code'.
- Individual considerations necessary:
 - Model experiments, CFD investigations, ...



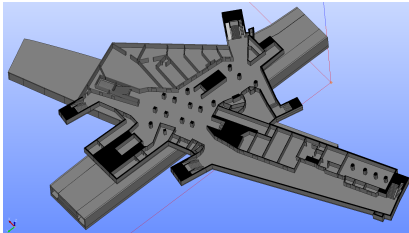
Figure: Interior of BMW World, Munich.

Motivation: Project Orpheus



Optimierung der **R**auchableitung und **P**ersonenführung in
U-Bahn**h**öfen: **E**xperimente **u**nd **S**imulationen

- Smoke and fire spread in complex metro stations.
 - High dimensional parameter space for fire scenarios, including underground climate.



Modeling fires

Processes to model:

- Fluid dynamics.
 - Navier–Stokes equations.
 - Turbulence modeling.
- Radiation.
 - Discrete Transfer Radiation.
 - Discrete Ordinates.
 - Monte–Carlo.
- Combustion
 - Mixture fraction.
 - Finite rate kinetics.
- Pyrolysis.

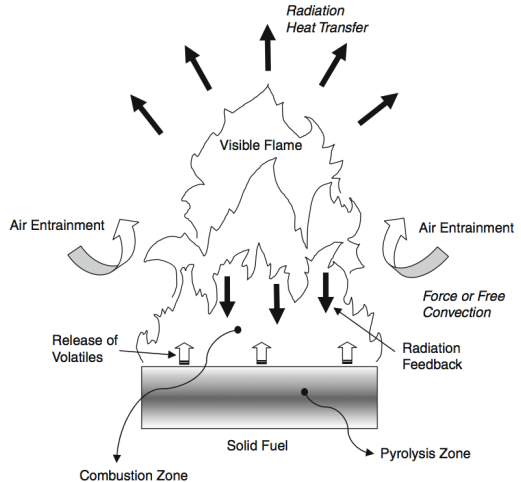


Figure: Burning solid fuel in air with physical processes involved. [1]

Modeling: Equations for smoke propagation

- Smoke propagation with incompressible Navier–Stokes (INS) equations:

$$\nabla \cdot \mathbf{u} = 0$$

$$\rho_0 [\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla) \mathbf{u}] + \nabla p - \nabla (2 \mu \epsilon_{ij}(\mathbf{u})) = \mathbf{f}(T)$$

$$\rho_0 [\partial_t T + (\mathbf{u} \cdot \nabla) T] - 2 \frac{\mu}{c_p} \epsilon_{ij}(\mathbf{u}) : \nabla \mathbf{u} - \nabla \cdot \left(\frac{\mu}{Pr} \nabla T \right) = \gamma$$

with strain rate tensor $\epsilon_{ij}(\mathbf{u}) = \frac{1}{2} [\nabla \mathbf{u} + (\nabla \mathbf{u})^T]$.

- Turbulence model: Smagorinsky–Lilly LES [2]:

$$\nu = \nu_{mol} + \nu_{turb} \quad \text{with} \quad \nu_{turb} = (C_s h)^2 \|\epsilon_{ij}(\mathbf{u})\|_2.$$

Numerical methods

Spatial discretization methods for computational fluid dynamics and software packages using it:

- Finite Difference Method (FDM).
 - [Open source](#): NIST Fire Dynamics Simulator (FDS), ...
- Finite Volume Method (FVM).
 - [Open source](#): FireFOAM (OpenFOAM), ...
- Finite Element Method (FEM).
- Lattice–Boltzmann Method (LBM).

FEM: Features

Why use FEM?

- Unstructured grids.
 - Allow for better domain representation without aliasing.
- hp-adaptivity.
 - Dynamic resolution of numerical grid.
 - Adaptive polynomial degree of basis functions.
 - Increase accuracy where the action is happening!
- Discontinuous Galerkin (DG) methods.
 - Allow discontinuities across cell borders.
 - Continuous Galerkin (CG) methods unstable for advection like problems, thus require stabilization.

FEM: Formulation

- Solve variational equation from 'weak' formulation of the differential equation with bilinear form $a(u, v)$:

$$\exists u \in V : \forall v \in V : a(u, v) = f(v)$$

- Choose subspace V_h with basis w_i , out of which the approximate solution $u_h = \sum u_i w_i \in V_h$ will be constructed:

$$a(u_h, w_j) = \sum a(w_i, w_j) u_i = f(w_j) \rightarrow AU = F$$

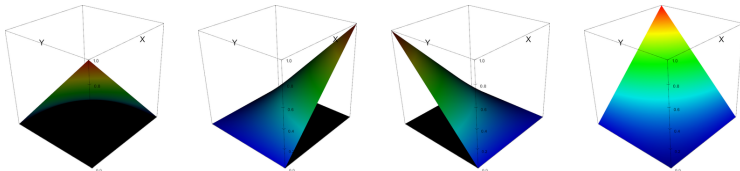


Figure: Q_1 elements in 2D (source: [deal.II](#))

JuFire



- Investigate applicability of Finite Element Methods (FEM) for fire simulation.
- Use open-source library deal.II [3].
 - 'Toolbox' for the creation of FEM codes.

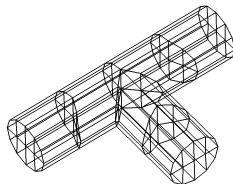


Differential **E**quations **A**nalysis **L**ibrary

JuFire: Features

Implemented:

- Unstructured grids.
- Continuous Galerkin Methods.
- Adaptive mesh refinement (AMR).
- MPI parallelization.
- Utilization of CAD models as manifolds for mesh refinement.

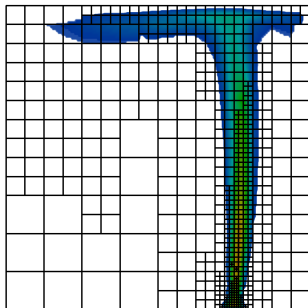


Current field of activity:

- Verification of flow solver.

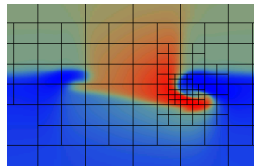
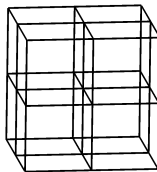
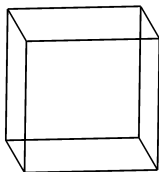
Future work:

- Discontinuous Galerkin methods.
- p-adaptivity.



Adaptive mesh refinement (AMR)

- Solution of differential equations with *FEM* requires:
 - Discretization of space in cells of length h .
 - Shape functions with polynomial degree p .
 - But: The more accurate the solution by choosing h and p , the longer the computation.
- **Adaptive refinement** as a 'compromise'.
- Adjustment of parameters locally where necessary.
 - Variable mesh precision at runtime.



J. Dreher, RUB

AMR: Algorithm

How to determine refinement criteria?

Set up decision criterion for refinement/coarsening.

Our choice:

- Calculate $||\nabla u||$ on each cell.
- Normalize values with respect to all cells.
- Flag top/lower 30% for refinement/coarsening at each step.
- Define max/min refinement levels as upper/lower bounds.
- Cells are not allowed to differ by more than one level of refinement.

AMR: Example

- Demonstration of adaptive mesh refinement via moving vortex test case as a shape-preserving potential stream.

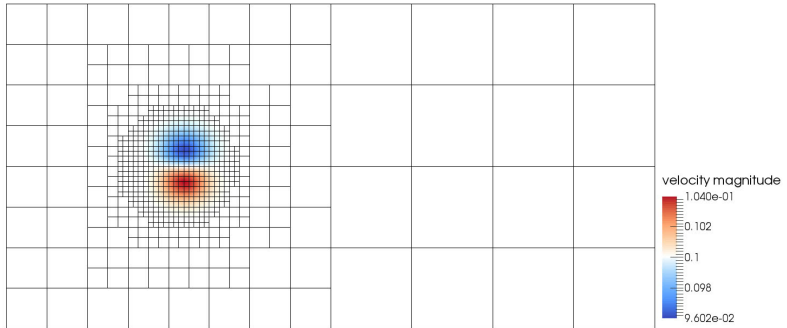


Figure: Video of velocity magnitude of moving vortex, overlaid with corresponding mesh.

AMR: Benefits

- Comparison of runtime and accuracy between uniform and adaptively refined meshes with the moving vortex example.

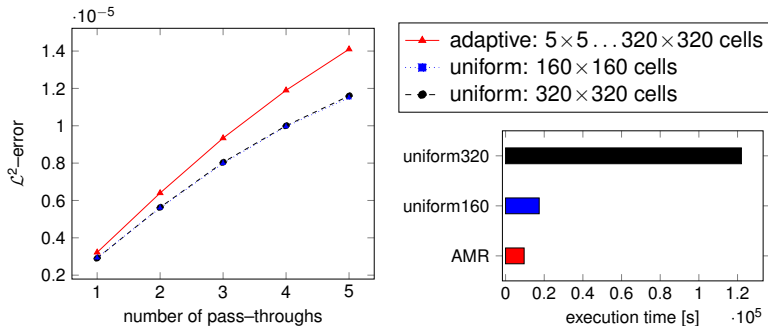


Figure: Global \mathcal{L}^2 -errors at each periodic pass-through of the vortex.

Figure: Execution time of the vortex simulation, run in serial on a common desktop computer.

HPC on JURECA: Parallelization

- MPI parallelization with Trilinos and p4est through deal.II backends.

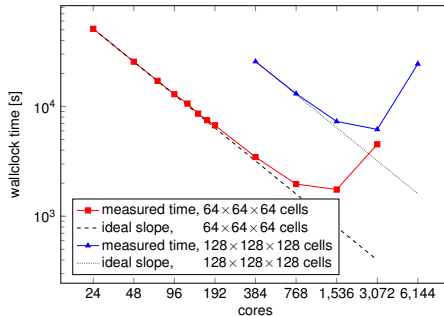


Figure: Strong scaling on JURECA for fixed 3D problems with 262,144 and 2,097,152 cells, respectively.

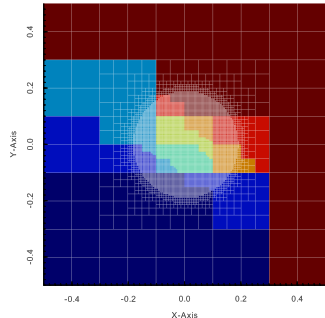


Figure: Exemplary domain decomposition with p4est in an AMR case.

Summary & Outlook

Summary:

- Adaptive Mesh Refinement works satisfactorily (for now).
- Flow solver accomplishes first verification tests.

Future work:

- Implementation of models.
 - Buoyancy, radiation, combustion, pyrolysis, ...
- Extension of numerical methods.
 - DG methods, p-adaptivity, ...
- Comparison with other fire solvers.
- Validation using experiments.

Thank you for your kind attention!

References I



Guan Heng Yeoh and Kwok Kit Yuen.
*Computational Fluid Dynamics in Fire Engineering –
Theory, Modelling and Practice.*
Butterworth–Heinemann, 1st edition, 2009.



Joseph Smagorinsky.
General circulation experiments with the primitive
equations.
Monthly Weather Review, 91(3):99–164, March 1963.

References II



W. Bangerth, D. Davydov, T. Heister, L. Heltai,
G. Kanschat, M. Kronbichler, M. Maier, B. Turcksin, and
D. Wells.

The deal.II library, version 8.4.

Journal of Numerical Mathematics, 24, 2016.



Cedric Taylor and P. Hood.

A numerical solution of the Navier–Stokes equations
using the finite element technique.

Computers & Fluids, 1:73–100, 1973.

References III



Bernardino Roig.

One-step Taylor Galerkin methods for convection-diffusion problems.

Journal of Computational and Applied Mathematics,
204:95–101, 2007.



N.D. Heavner and L.G. Rebholz.

Locally chosen grad-div stabilization parameters for finite element discretizations of incompressible flow problems.

SIAM Undergraduate Research Online (SIURO), 7.

Fein oder nicht fein: Anhang

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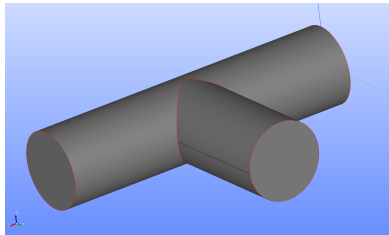
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JuFire: Algorithm

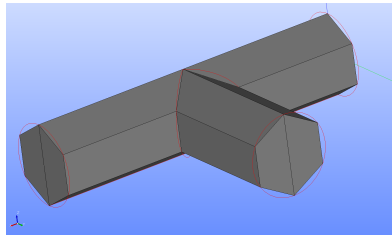
- Time evolution with backward differentiation formula (BDF)
- Taylor–Hood elements [4]: $(\mathbf{u}, p) \in Q_{k+1}^{\text{dim}} \times Q_k$
- Decoupling of (\mathbf{u}, p) by projection scheme
 - Leads to the pressure–Poisson equation
- Stabilization of momentum equation
 - Taylor–Galerkin stabilization [5] for Taylor–Hood elements
 - Additional diffusion in flow direction
 - Grad–div stabilization [6] to enforce $\nabla \cdot \mathbf{u} = 0$
- Neumann series for fast matrix assembly
- Boussinesq approximation for buoyancy force density

Unstructured Grids: Example: T-pipe

- Why T-pipe?
 - Compound bodies.
 - Crooked areas (→ cylinder casing area).
 - Discontinuous edges (→ 'welding seam').
- Develop procedure for the creation of appropriate initial meshes.



CAD model.



Initial mesh.

Iterations of global refinement:

